150 Years of Rowing Faster!

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Oxford-Cambridge Boat Race
Winning Times 1845-2009
FISA Men’s championship 1x Winning Times 1894-2009
25-30% increase in average velocity over 150 years of competitive rowing

What are the performance variables and how have they changed?

How will future improvements be achieved?
Decrease Power Losses

- Decrease Drag Forces on Boat
- Increase Propulsive Efficiency of oar/blade
- Improve Technical Efficiency

Increase Propulsive Power

- Increase Propulsive Power
- Aerobic Capacity
- Anaerobic Capacity
- Maximal Strength
- Improved Training

Increased Physical Dimensions
Decrease Power Losses

Increase Propulsive Power

Aerobic Capacity

Decrease Drag Forces on Boat

Anaerobic Capacity

Increase Propulsive Efficiency of oar/blade

Improved Training

Increase Physical Dimensions

Maximal Strength

Improve Technical Efficiency

Increase Propulsive Power
“Evolutionary Constraints”

- Race duration ~ 6-7 minutes
- Weight supported activity
- Oar geometry dictates relatively low cycle frequency and favors large stroke distance to accelerate boat
- High water resistance decelerates boat rapidly between force impulses
These constraints result in:

- High selection pressure for height and arm length
- High selection pressure for \textit{absolute} (weight independent) aerobic capacity
- Significant selection pressure for muscular strength and anaerobic capacity
Ned Hanlan ca 1880
173cm
71kg

Biglin Brothers ca 1865
180cm? 75-80kg?

Ward Brothers ca 1865
185cm?
80+kg?
“Since the 19th century there have been clearly documented secular trends to increasing adult height in most European countries with current rates of 10-30mm/decade.”

97th percentile for height in Dutch 21 year-olds

Taller Population = Taller Elite Rowers

Oxford Crew-2005
Average Height: 197cm
Average bodyweight: 98.3 kg
Scaling problems- Geometry or fractal filling volumes?

Based on Geometric scaling:
Strength and VO$_2$ max will increase in proportion to mass$^{2/3}$.

BUT, Metabolic rates of organisms scale with mass$^{3/4}$.

$\text{VO}_2$ body mass scaling in elite rowers

Relationship between maximal oxygen uptake and body mass for 117 Danish rowers (national team candidates)

Measuring Rowing Specific Physical Capacity

Photo courtesy of Mathijs Hofmijster, Faculty of Human Movement Sciences, Free University Amsterdam, Netherlands
photos 1-4 from Miller, B. “The development of rowing equipment” http://www.rowinghistory.net/equipment.htm
The Maximum of Human Power and its Fuel

From Observations on the Yale University Crew, Winner of the Olympic Championship, Paris, 1924

Crew average:
Height: 185 cm
Weight: 82 kg

Henderson, Y and Haggard, H.W. American J. Physiology. 72, 264-282, 1925
Estimated external work required at racing speed based on:

1. Boat pulling measurements
2. Work output on a rowing machine
3. Rowing ergometer VO₂ measurements (but did not go to max)

Estimated an external work requirement of ~6 Calories/min or (assuming 20% efficiency)
30 Calories/min energy expenditure.

Equals ~ 6 Liter/min O₂ cost

Assumed 4 L/min VO₂ max and 2 L/min anaerobic contribution during 6 min race.

The ergometer of the day had to be redesigned to allow a quantification of work and power.
1970s - VO₂ max vs boat placement in international regatta

193 cm, 92 kg 6.23 L/min VO₂ cycling. Subject reached 6.1 to 6.4 L/min during repeated testing in different boats.

Aerobic Capacity Developments

VO₂ max (L/min)

Year

1860 1910 1960 2010

7+ L/min

Dr. Fred Hagerman
Ohio University
“Typical World Class” XC skiers

6.3 L/min, 75 kg, 85 ml/kg/min, 270 ml/kg\(^{0.73}\)/min

Allometrically equivalent rower?

7.5 L/min, 95 kg, (not measured) 79 ml/kg/min, 270 ml/kg\(^{0.73}\)/min
How much of performance improvement is attributable to increased physical dimensions?

Based on W Cup results from Lucerne over:

- 3 years
- 3 boat types
- 1st 3 places

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Velocity (m/s)
A Day's Training.

Rise at 7 a.m: Run 100-200 yards as fast as possible

Exercise (forenoon).
Dinner about 2 p.m.

Tea, two cups, or towards the end of training a cup and a half only.
Watercresses occasionally.
None.
Meat, Beef or Mutton.
Bread.
Vegetables — Potatoes, Greens.

About 5:30: Start for the river and row for the starting post and back

Bed at 10.0

Watercresses.
Beer, one pint.

Reckoning a half an hour in rowing to and half an hour from the starting point, and a quarter of an hour for the morning run— in all, say, one and a quarter hours.
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<td>3 sets 4 x 4 min</td>
<td>ON/1 min OFF in pairs</td>
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US National Team training during peak loading period

3 sessions/day
30+ hr/wk

From US Women’s national team 1996
Developments in training over last 3 decades

Winter
Summer

70s 80s 90s

5.8 l·min⁻¹ 6.4 l·min⁻¹ 6.5 l·min⁻¹
924 hrs·yr⁻¹ 966 hrs·yr⁻¹ 1128 hr·yr⁻¹

Fisherstrand A, Seiler KS
Developments in training over last 3 decades

1860s - “Athletes Heart” debate begins

- **1867**- London surgeon F.C. Shey likened The Boat Race to cruelty to animals, warning that maximal effort for 20 minutes could lead to permanent injury.

- **1873**- John Morgan (physician and former Oxford crew captain) compared 251 former oarsmen with non-rowers - concluded that the rowers had lived 2 years longer!

- Myocardial hypertrophy was key topic of debate, but tools for measurement (besides at autopsy) were not yet available.


*See also: Thompson P.D. Historical aspects of the Athletes Heart. MSSE 35(2), 364-370 2003.*
Big-hearted Italian Rowers - 1980s

- Of 947 elite Italian athletes tested, 16 had ventricular wall thicknesses exceeding normal criteria for cardiomyopathy. 15 of these 16 were rowers or canoeists (all international medalists).

- Suggested that combination of pressure and volume loading on heart in rowing was unique, but adaptation was physiological and not pathological.

From: Pelliccia et al. Global left ventricular shape is not altered as a consequence of physiologic remodelling in highly trained athletes. Am. J. Cardiol. 86(6), 700-702, 2000
Myocardial adaptation to heavy endurance training was shown to be reversed with detraining.

The functional and morphological changes described as the "Athlete’s Heart" are adaptive, not pathological.

Pelliccia et al. Remodeling of Left Ventricular Hypertrophy in Elite Athletes After Long-Term Deconditioning *Circulation*. 105:944, 2002
Force production and strength in rowing

- Ishiko used strain gauge dynamometers mounted on the oars of the silver medal winning 8+ from Tokyo 1964 to measure peak dynamic forces.
- Values were of the magnitude 700-900 N based on the figures shown

How Strong do Rowers need to be?

1971 - Secher calculated power to row at winning speed in 1972 championships = 450 watts (2749 kpm/min)

“\textit{In accordance with the force-velocity relationship a minimal (isometric) rowing strength of } 53 \div 0.4 = 133 \text{ kp (1300N)} \text{ will be essential.}”

Force production and rowing strength

Measured isometric force in 7 Olympic/world medalists, plus other rowers and non-rowers

Average peak isometric force (mid-drive): 2000 N

No correlation between "rowing strength" and leg extension, back extension, elbow flexion, etc.

Decrease Power Losses

Increase Total Propulsive Power

- Aerobic Capacity
- Anaerobic Capacity
- Improved Training
- Maximal Strength
- Physical Dimensions?

Decrease Drag Forces on Boat

Increase Propulsive Efficiency of oar/blade

Improve Technical Efficiency
Decrease Power Losses

Decrease Drag Forces on Boat

Increase Propulsive Efficiency of oar/blade

Improve Technical Efficiency
Boat Velocity – Oxygen Demand Relationship

Oxygen Demand (l/min)

1x Boat Velocity (m/sec)

Boat velocity range for Men’s and women’s 1x
Drag Forces on the Boat and Rower

- **Skin (Surface) Drag** - 80% of hydrodynamic drag (depends on boat shape and total wetted surface area)

- **Wave drag contribution small** - <10% of hydrodynamic drag

- **Air resistance** – normally <10% of total drag, depends on cross-sectional area of rowers plus shell
In-rigged wherry typical of those used in racing prior to 1830

figures from Miller, B. “The development of rowing equipment”
http://www.rowinghistory.net/equipment.htm
All radical boat form improvements completed by 1856.

- 1828-1841. Outrigger tried by Brown and Emmet, and perfected by Harry Clasper

- Keel-less hull developed by William Pocock and Harry Clasper 1840-1845

- Thin-skin applied to keel-less frame by Matt Taylor- 1855-56

- Transition to epoxy and carbon fiber boats came in 1972. Boat weight of 8 reduced by 40kg

photo and timeline from Miller, B. “The development of rowing equipment” http://www.rowinghistory.net/equipment.htm
Effect of reduction in **Boat Weight** on boat velocity

\[ \frac{\Delta V}{V} = -(1/6) \frac{\Delta M}{M_{total}} \]

Example: Reducing boat+oar weight from 32 to 16kg = 2.4% speed increase for 80 kg 19th century rower.

To achieve a radical reduction in drag forces on current boats, they would have to be lifted out of the water!
Flyak hydrofoil video
Decrease Power Losses

Decrease Drag Forces on Boat

Increase Propulsive Efficiency of oar/blade

Improve Technical Efficiency
Oar movement translates rower power to boat velocity

Figure from:
ROWING PARAPHERNALIA are described in the 1871 edition of "Catalogue and Oarsman's Manual." Items include a close-grain ash oar, an oarsman with greased leather trousers to slide—the "bucks"—and a "rudder."
The slide properly used is a decided advantage and gain of speed, and only objection to its use is its complication and almost impracticable requirement of skill and unison in the crew, rather than any positive defect in its mechanical theory.

J.C. Babcock  1870


Boat direction

Photo from www.concept2.com
Oar hydrodynamic efficiency - propelling the boat but not the water

\[ E_{\text{hydro}} = \text{Power applied}_{\text{rower}} - \text{Power loss}_{\text{moving water}} \]

\[ \text{Power applied}_{\text{rower}} \]

\[ \text{Power applied} = \text{Force Moment at the oar} \times \text{oar angular velocity} \]

\[ \text{Oar power loss} = \text{blade drag force} \times \text{blade velocity (slip)} \]

Oar Evolution

Square loomed scull 1847

"Square" and "Coffin" blades 1906

Macon blade - wooden shaft 1960-1977


Cleaver blade - ultra light carbon fiber shaft 1991-
Big blades found to be 3% more hydrodynamically efficient compared to Macon blade.

Rower/tinkerer/scientists?-
The Dreissigacker Brothers

Dick Dreissigacker testing an early oar design.

All pictures from www.concept2.com in exchange for unsolicited and indirect endorsement!
Effect of Improved Oars on boat speed?

• Kleshnev (2002) used instrumented boats and measurement of 21 crews to estimate an 18% energy loss to moving water by blade

• Data suggests 2-3% gain in boat velocity possible with further optimization of oar efficiency (30-50% of the present ~ 6% velocity loss to oar blade energy waste)
Rowing Technique: “Ergs don’t float”
Decrease Power Losses

Decrease Drag Forces on Boat

Increase Propulsive Efficiency of oar/blade

Decrease velocity fluctuations

Minimize Boat Yaw, Pitch and Roll

Optimize/Synchronize Force Curves
Decreasing Velocity Fluctuations

Sources

- Pulsatile Force application
- Reactions to body mass acceleration in boat

Larger fluctuations require greater propulsive power for same average velocity

Figure from Affeld et al. Int. J. Sports Med. 14: S39-S41, 1993
The Sliding Rigger

- Idea patented in 1870s
- Functional model built in 1950s
- Further developed by Volker Nolte and Empacher in early 1980s
- Kolbe won WCs in 1981 with sliding rigger
- Top 5 1x finalists used sliding rigger in 1982.
- Outlawed by FISA in 1983 due to “high cost”.

1954 Sliding Rigger developed by C.E. Poynter (UK)

How much speed could be gained by reducing velocity fluctuations by 50%?

- Estimated $\sim 5\%$ efficiency loss due to velocity fluctuations (see Sanderson and Martindale (1986) and Kleshnev (2002))

- Reducing this loss by 50% would result in a gain in boat velocity of $\sim 1\%$ or 4-5 seconds in a 7 minute race.

- **Sliding rigger effect probably bigger!**
  due to decreased energy cost of rowing and increased stability (an additional 5s ?)
Better Boat Balance?

**Yaw**
- 0.1 to 0.6 degrees.
- 0.5 degrees = 2.5 cm bow movement

**Pitch**
- 0.3 to 0.5 degrees
- 50% of variability attributable to differences in rower mass

**Roll**
- 0.3 to 2.0 degrees.
- Highest variability between rowers here

Smith, R. Boat orientation and skill level in sculling boats. Coaches Information Service http://coachesinfo.com/
"Oarsmen of a crew try to row in the same manner and they believe that they are doing so. But from the data it may be concluded that this is actually not true."

A “Good Crew”

“A new crew with visible success”

2 juniors with “only 1 year experience in the same boat”

Rowing Together: Synchronizing force curves

Fatigue changes the amplitude of the curve, but not its shape.

Changing rowers in the boat did not change the force curves of the other rowers, at least not in the short term.

Is there an optimal force curve?

- **For a 1x sculler:** perhaps yes, one that balances hydrodynamic and physiological constraints to create a personal optima.
- **For a team boat:** probably no single optima exists due to interplay between biomechanical and physiological constraints at individual level.

Contribution of rowing variables to increased velocity over 150 years

- Improved Training – 33%
- Improved hydrodynamic efficiency of oar – 25%
- Improved Boat Design /reduced dead weight – 12%
- Increased Physical Dimensions - 10%
- Sliding Seat/Evolved Rowing Technique – 20%